Price Formation of Exhaustible Resources: An Experimental Investigation of the Hotelling Rule[1]

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Abstract

In 1931 Harold Hotelling published his seminal contribution to the economic theory of exhaustible resources. His major insight states that the prices of exhaustible resources - more specifically the scarcity rent - will rise at the rate of interest, and consumption will decline over time. The equilibrium implies social optimality. However, empirical analysis shows that market prices of exhaustible resources rarely follow the predicted pattern. Yet our experimental investigation provides support for the position that the Hotelling rule is relevant for the long term development of resource prices.

JEL Classification:

Keywords: Exhaustible resource, Hotelling rule, Intertemporal Allocation Problem, Continuous Double Auction, Experiment

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1 Introduction

Harold Hotelling (1931) set the foundation of a formal theory regarding the use of non-renewable resources in his quite famous article "The Economics of Exhaustible Resources". The Hotelling rule states that, for an exhaustible resource, the difference between price and marginal cost – the scarcity rent[4] – should rise at the rate of interest. Then, a resource owner is indifferent between extracting the last marginal unit of the resource now or in the future.

The finding from Hotelling is still the central concept in the field of resource economics literature. Nevertheless declining real market prices repeatedly seem to contradict the simple model logic. Figure 1 shows price paths for oil, gas and coal, and illustrates divergence from the theory.

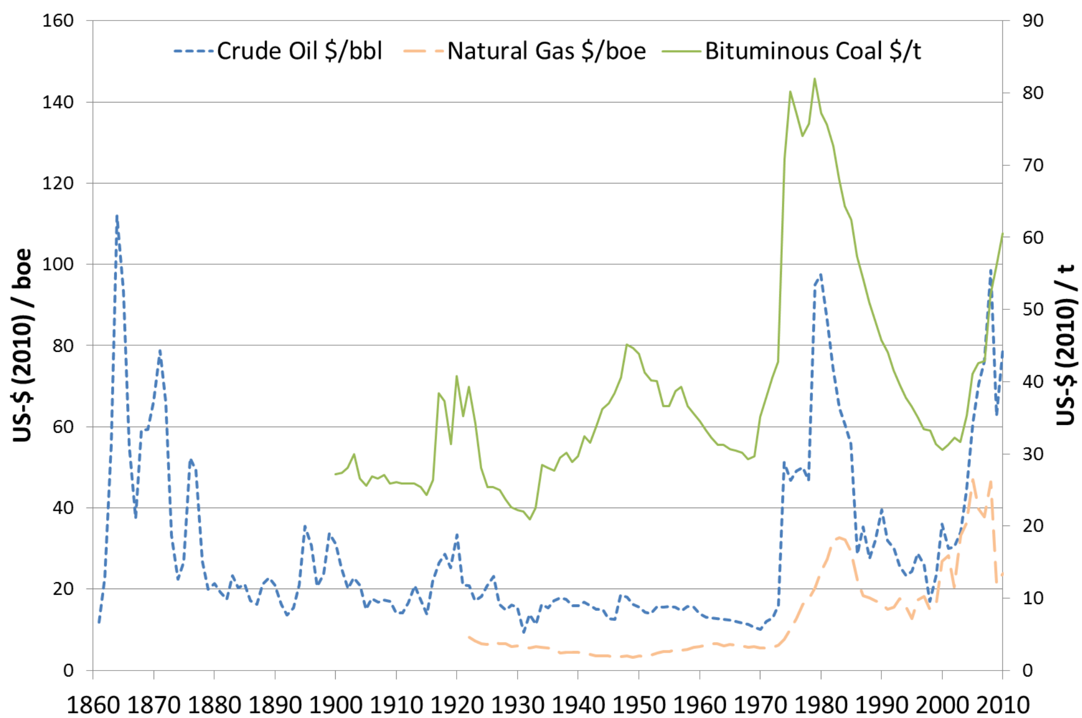

Figure 1 Price development in the long run for crude oil, coal and gas. Real prices deflated by CPI. Data Source: BP (Oil, CPI), IEA (Coal 1972-2010, Gas), NMA (Coal 1900-1971)

Figure 1 shows that the corresponding resource prices do not follow the predicted exponential growth pattern of Hotelling's theory. In contrast, we find phases of decreasing

[4] In the literature are several terms used which can be viewed as synonyms: (marginal) user cost, Hotelling rent, dynamic rent, royalty, net price, shadow price or co-state variables (in terms of optimal control theory). We will use the term scarcity rent in the following.

and phases of increasing prices as well as many short term fluctuations. This questions the validity of the basic model. Even more, one may ask: What is the value of a theory which is not observable in markets and perhaps even by the behavior of humans? Following Allais thoughts in his Nobel prize speech, he believes that "a theory which cannot be confronted with the facts or which has not been verified quantitatively by observed data, is devoid of any scientific value" (Allais 1988, p. 243).

Our assessment is that the common approaches for testing Hotelling's model have severe data problems so that seemingly negative results are not sufficient for a definite rejection of the Hotelling model. Our objective is to gain further insights into the empirical validity of this theory by using the method of experimental economics. In particular, we test whether the subjects in our experiment behave in accordance with the logic of Hotelling's model and whether they are able to solve this intertemporal dynamic allocation problem. We find that the auction prices as well as the traded volume are, by and large, in accordance with the theory.

The significance of this study is its contribution to the testing of the Hotelling Rule as the theoretical framework of exhaustible resource economics, which is the foundation of our understanding how exhaustible resource markets will respectively should evolve. To the best of our knowledge, this is the first time the Hotelling rule is implemented in a competitive market environment within a controlled continuous double auction set-up.

The paper is organized as follows. Section 2 briefly describes the previous literature with a focus on empirical testing studies. Section 3 describes the experimental design and the procedures. Section 4 provides the hypotheses followed by the results in Chapter 5. Chapter 6 contains a brief discussion about deviations from the theory. The final section offers conclusions and ideas for further research.

2 Previous empirical studies

Before the 1970s economists were not greatly interested in Hotelling's findings. Regarding the empirical work, only two Resource of the Future studies can be find from Potter and Christy (1962) as well as the more famous one from Barnett and Morse (1963) which analyze long-run price trends. Although the latter study bore only a little relationship with Hotelling´s theory (Lasserre 2013), they find that real prices did not show an upward trend (Barnett and

Morse 1963). With the upcoming energy price shocks, exhaustible resource models gained a lot of attention during the 1970s. So far, theoretical studies entered the focus of many economists (e.g. Dasgupta and Heal, 1974; Solow, 1974; Stiglitz 1974).

In the 1980s, a series of empirical studies investigated the price formation process of exhaustible resources. Still today, researchers try to explain data sets with a Hotelling-related framework. We want to classify the empirical results of the literature into three categories.[5] The first includes studies which reject the theory.

Heal and Barrow (1981) analyze the relationship between metal price movements and levels of interest rates but find no correlation and conclude that Hotelling´s theory cannot be validated. Farrow´s results are inconsistent with the theoretical Hotelling model using data from a mining firm (Farrow 1985). Furthermore, the firm´s behavior could not be explained by extending the basic model with a time-varying discount rate, an alternative expected price series and a constraint on the rate of output. In the empirical studies of Miller and Upton (1985a and 1985b) the Hotelling rule is reformulated into the relatively less known Hotelling Valuation Principle (HVP) which states that the market value of a resource in the ground equals its current net price. However, the authors caveat their findings as being based on less than three years of data. While they find empirical support in their first study, they have to acknowledge that the data in the second study differs significantly from the theory (Miller and Upton 1985b). Furthermore, Adelman and Watkins argue that the HVP has to be rejected for both theoretical and empirical reasons (Adelman 1990, Watkins 1992). Halvorsen and Smith (1991) also strongly reject the empirical implications of Hotelling using a direct test with an econometric model and data from the Canadian metal mining industry. Further, Young (1992) extends Farrows work concerning the cost function specifications and with a more extended data set. Also, his results do not withstand empirical scrutiny. Young and Ryan (1996) incorporate risk to an industry-level Hotelling model of resource extraction. Although they believe that the approach to consider risk aspects is improving the performance, the historical price behavior cannot be explained sufficiently by their model. Adelman and Watkins (2008) see no upward trend in energy prices and conclude that the Hotelling paradigm conflicts with their data. They are criticizing the premise of a limited known in-

[5] Due to the huge number of papers discussing, using and testing this model, the following review does not have the purpose of providing a complete survey.

ground stock. Leinert (2010) tests the effect of unanticipated oil field discoveries. Following the theory one should expect a significant adjustment of the resource price but this was not observed in the study.

Our second category consists of papers with less clear and straightforward results. Slade (1982) develops a model which is consistent with the Hotelling rule although it suggests a u-shaped price path due to the implementation of technological change. The author distinguishes three different phases in a lifecycle of exhaustible resources - falling, stable and rising prices - by examining empirical evidence from 11 different metal and fuel types. However, this result bears methodological criticism (Livernois 2009) because Berck and Roberts (1996) find evidence of unit roots in the price series. However, this finding is again refuted by Lee, List and Strazicich (2006). They find evidence against the unit root hypothesis. Furthermore, by allowing for structural breaks, natural resource prices seem to be stationary around deterministic trends. Nevertheless, Livernois (2009) concludes from the work of Lee et al. (2006) that any general conclusions about whether prices are rising or falling are impossible.

Stollery (1983) applies a Hotelling-type depletion model to the nickel industry and finds that the model explains the behavior of the industry well, since depletion has been an important determinant of prices. However, Hart and Spiro (2011) criticize that Stollery uses the only time period where nickel prices have been increasing. Slade and Thille (1997) derive a model which integrates the Hotelling model and the Capital-Asset-Pricing Model. Although they could not reject the Hotelling model, the results are overshadowed by implausible effects.[6]

In contrast to the aforementioned literature, there are a considerably low number of empirical studies that fail to reject the theory. The last category consists only of a few studies, which are – as far as we know – the only studies, which are not criticized for e.g. methodology or data reasons. Berck and Bentley (1997) publish a study about old-growth redwood, which can be widely regarded as an exhaustible resource, due to the length of its lifecycle. They show that the data does not contradict the theory. Also Livernois, Thille and Zhang (2006)

[6] E.g. the degree of diversification, β, that is required to obtain reasonable signs and modest significance for the Hotelling coefficients seems to their own declarations "too large to be believable" (Slade and Thille 1997, p. 703).

conduct a study with old-growth timber and find consistency with a modified Hotelling rule. The major advantage in both studies is that a measure of scarcity rent is directly observable in the form of stumpage price bids in timber auctions.

Certainly, one has to consider that a rejection of a particular model is usually a rejection of a certain variant with a limited data set for a particular resource. Consequently one cannot claim an absolute rejection [or confirmation] of the theory based on one study. However despite the improvement of statistical methods and extensions of the simple basic model to more complex ones, overall one has to admit that the theoretical framework from Hotelling in exhaustible resource models has only earned little empirical support.

Furthermore, from this literature review we have to acknowledge that there are at least two main problems within the traditional research methodology.

First, a theory can only be verified if its assumptions are met adequately. In the complex, real world there are several factors influencing the prices and allocation of exhaustible resources markets. Consequently the assumptions of the model, such as a constant and known stock or a constant interest rate, are violated. Livernois (2009, p. 37) states that only by controlling for all relevant factors "do we have a credible chance of refuting or supporting the Hotelling rule", which is still an unsolved task. Second, the data availability is consistently interfering. The development of the scarcity rent is of primary interest for the analysis. Since market prices are aggregated values of several components, scarcity rent is usually unobservable and, instead, must be estimated. This data issue usually remains because vertically integrated companies rarely publish the required data.

A another empirical concern is that, if the scarcity rent is very small, as would be the case with a relatively abundant resource endowment, it could be under a threshold of measurability, although it is a component of the price.

To summarize, we can distinguish between four different types of testing approaches.[7] First, there are descriptive studies which examine the price behavior (e.g. Barnett and Morse (1963), Heal and Barrow (1981)). Second, a specific model can be tested by estimating equations, as per Farrow (1985) or Young (1992). This approach rely on econometric estimations focusing on the scarcity rent. The third approach refers to a reformulation of the Hotelling rule in the form of the HVP, starting with Miller and Upton (1985a). Finally, we want

[7] For more detailed descriptions of the first three types see Slade and Thille (2009).

to show with this study that the experimental approach has to be also mentioned as a possibility to investigate the theory of exhaustible resources. By using the experimental method, we meet all the above-mentioned obstacles by designing an artificial laboratory world and analyzing real human behavior facing economic theory. The use of the experimental method could be a complementary way of creating an added value, especially if other economic methods gain only limited insights or reach their limits. It is surprising that our study is one of the first to use this approach, which might be due to the fact that experimental research in economics has a relatively recent history. To our knowledge, there is only one recent working paper which contains related work (Veldhuizen and Sonnemans 2011). The focus of the aforementioned paper is to find a possible failure of the Hotelling rule. The authors discover that subjects are paying more attention to strategic behavior than to dynamic optimization aspects by varying the stock size. They conclude that resource owners may not behave like the Hotelling rule would predict regarding the relative abundance of many exhaustible resources in real markets.

3 Experimental Design and Procedures

Our experiment consists of a computerized continuous double auction (CDA) of an exhaustible resource lasting for 10 periods. Each period lasted for three minutes. In each auction market there were 10 buyers and 10 sellers. At the beginning of a market each seller was endowed with 50 homogeneous units of a depletable resource which they could sell during the 10 periods of a market. Any resource, however, that had not been sold after period 10 had a value of zero.

The buyers' valuations of the resource within each period were determined by a utility function

$$U_t = ax_t - \frac{1}{2}bx_t^2 = 20x_t - x_t^2.$$

Their period profit then was given by $U_t - \sum p_i$. The sellers' period profits were equal to their revenues $R_t = \sum p_i$. In addition, revenues from preceding periods yielded interest so that the sellers' profits at the end of period 10 were given by

$$\pi = \sum\nolimits_t R_t(1+r)^{10-t}.$$

Since the consumers' behavior in Hotelling's model is independent of the interest rate, we decided not to pay interest to the buyers. This made it easier for the participants to assess their trades.

The trading procedure corresponds to the usual design of continuous double auctions: at any time they wished, sellers and buyers could place offers and bids, respectively. All offers and bids were public but the players placing the offers and bids remained anonymous. Sellers' offers were only accepted if the corresponding supply price was below the current best offer. In the same way buyers' bids were only accepted if they were greater than the current best bid.

Sellers (buyers) could accept the current best bid (best offer) by clicking an "accept button". An alternative way of concluding a contract consisted of placing an offer (bid) that was below (above) the current best bid (best offer). Such an offer triggered exactly the same transaction as clicking the "accept button".

Because our experiment only has a rather short time horizon, we needed a high rate of interest in order to generate a dynamic equilibrium path with significantly different prices and quantities for each period. Thus, we have chosen an interest rate r of 20%.

Given the buyers utility function, the initial endowment of the exhaustible resource and the interest rate of 20%, equilibrium prices are given by the following equation:

$$p_t = 3.852 \cdot 1.2^{t-1}.$$

Trades can only be conducted for quantities of exactly one unit (each resource unit is auctioned off separately) and the corresponding buyers' marginal utilities in discrete steps are given by 19, 17, 15, … In equilibrium, in each period buyers will buy additional units of the resource until marginal utility becomes smaller than the market price. The corresponding equilibrium prices and quantities are given in table 1. Accordingly, prices will increase exponentially and quantities will decrease.

Table 1 Dynamic equilibrium path of our market for the exhaustible resource.

Period	Price	Individual quantities
1	3.852	8
2	4.622	8
3	5.548	7
4	6.656	7
5	7.988	6
6	9.856	5
7	11.502	4
8	13.804	3
9	16.564	2
10	––	0

Note that the individual quantities represent buyer quantities. Because the sellers are indifferent with respect to the timing of trades, the sellers' individual quantities may deviate from the buyers' quantities. From a market perspective it is only important that the aggregate sales in each period are equal to the market quantities. Finally, note that this equilibrium is efficient from a social point of view.

Our experiment consists of only one treatment which has been conducted in five sessions. In each of these sessions the subjects participated in two markets so that they had an opportunity for learning. 20 subjects participated in each session, 10 as buyers and 10 as sellers. Accordingly, the total number of participating subjects amounts to 100. Subjects were undergraduate and graduate students at Clausthal University of Technology.

Participants were randomly assigned to their roles as buyers and sellers and kept their role in the second market of each session. On average, the sessions lasted for about 90 minutes and subject earned 18.65€ (ca. 25$).

The experiment was programmed in z-tree (Fischbacher 2007). At the beginning of each session we distributed written instructions, asked the students to read them carefully and then conducted a test of understanding. In order to get the student used to the program we let them play one training period. Finally, the experiment proper started.

4 Hypotheses

In the non-experimental literature, several authors (e.g. Pindyck 1981, Cairns 1986, Hartwick 1998, Livernois 2009) are skeptical of whether a resource owner does behave in the way that is assumed in a Hotelling-type model. Indeed, in the real world as well as in the laboratory there are no economic agents with perfect foresight, nor are there perfect future markets[8]. Instead of fully informed economic agents there are cognitively restrained subjects. Under such circumstances conducting dynamic optimization becomes a very difficult task. Many experimental studies have shown that it is too difficult for many of the subjects in economic experiments. Hey and Dardanoni (1987), Fehr and Zych (1998), Noussair and Matheny (2000), Kotlikoff et al. (2001), Carbone and Hey (2004), Hey and Knoll (2007), Bone and Suckling 2009, Brown et al. (2009), Ballinger et al. (2011) and Meissner (2013) report that laboratory behavior departs significantly from optimal behavior so that it looks naïve to expect a market behavior that is perfectly consistent with Hotelling's optimal path.

Yet the experimental literature on dynamic optimization also provides some arguments in favor of efficient behavior. Hey and Dardanoni (1987) and Carbone and Hey (2004) find that participants' behavior is in accordance with the comparative statics of optimal behavior. Allen and Carroll (2001), Ballinger et al. (2003), Ballinger et al. (2011), Chua and Camerer (2007) report that learning takes place and that it improves individual performance substantially. Finally, there is good reason to suppose that the market as an institution may serve as a substitute for individual rationality in order to induce a near-optimal performance. Smith (2003, pp. 469-471) calls this ecological rationality. Taking all this into account, we did not expect to find exact equilibrium play, but a sequence of prices and quantities being somewhat close to the equilibrium path. This leads us to our main five hypotheses.

Hypothesis 1 (increasing price path): *Prices will increase over the 10 periods.*

Hypothesis 1 claims that the development of prices will be (at least loosely) connected to the price path given by economic theory. A minimum requirement for the competent ability with economic theory is that prices have to increase over the periods.

[8] A perfect future market refers to the assumption of concluding today optimal contracts till infinity.

Hypothesis 2 (learning): *The market performance in the second market of each session will be closer to the equilibrium path than the performance in the preceding market*.

The experiments on individual dynamic optimization behavior often show strong learning effects. We expected to find similar effects in our second markets because of the additional experience that the participants would gain during the first market in each session. Since all participants could only play two markets in each session, we were rather uncertain about the magnitude of the learning effects.

Hypothesis 3 (exponential growth path): *The price path over the 10 periods will have a convex curvature that is largely in accordance with the exponential growth path of Hotelling's model*.

Compared to hypotheses is 1, hypothesis 3 states an enhanced predictive power of the standard theory of exhaustible resources. Prices not only increase over time but they increase by a continuously rising amount.

Hypothesis 4 (decreasing quantities): *In each market, consumption quantities decrease over time so that (a) the entire stock will be depleted after 10 periods and (b) there will be no trades in the final period*.

Hypothesis 4 describes the central qualitative features of the equilibrium consumption path. Because prices are rising, the consumption quantities will fall. Furthermore, since all remaining resources after period 10 are worthless, the entire stock will be sold to the consumers. Finally, due to a sufficient degree of scarcity and the high interest rate, the entire stock will already be sold out in period 9.

Hypothesis 5 (high-efficiency): *The overall efficiency of the markets will be comparatively high. It will typically be significantly above 90%*.

In countless experiments the institution of the CDA-market has shown to provide surprisingly high degrees of efficiency. After only very few periods of learning (most often just one period), the efficiency is typically significantly above 90%. We expected this results to hold in our experiment, too.

5 Results

The aim of this study is to investigate whether humans behave in accordance with the Hotelling model and if it is able to solve this intertemporal dynamic allocation problem within a market environment. Therefore, we are testing whether the central statements of exhaustible-resource theory is evidential both in a qualitatively and quantitatively way.

Result 1: An increasing price path.

Since we know from the literature that intertemporal decisions are challenging, and that the subjects are confronted with different optimal price-quantity combinations in each period, there are doubts about whether the theoretical framework would hold true in the laboratory. However, we find that, in accordance with the theory, the auction prices are in a monotonically increasing sequence with a view to the median transaction prices. This statement is valid for the price formation of the aggregated 10 markets, as shown in Figure 2. The dashed line represents the optimal price path calculated by the theoretical framework in Chapter 3. The crosses represent the period-wise median transaction price.

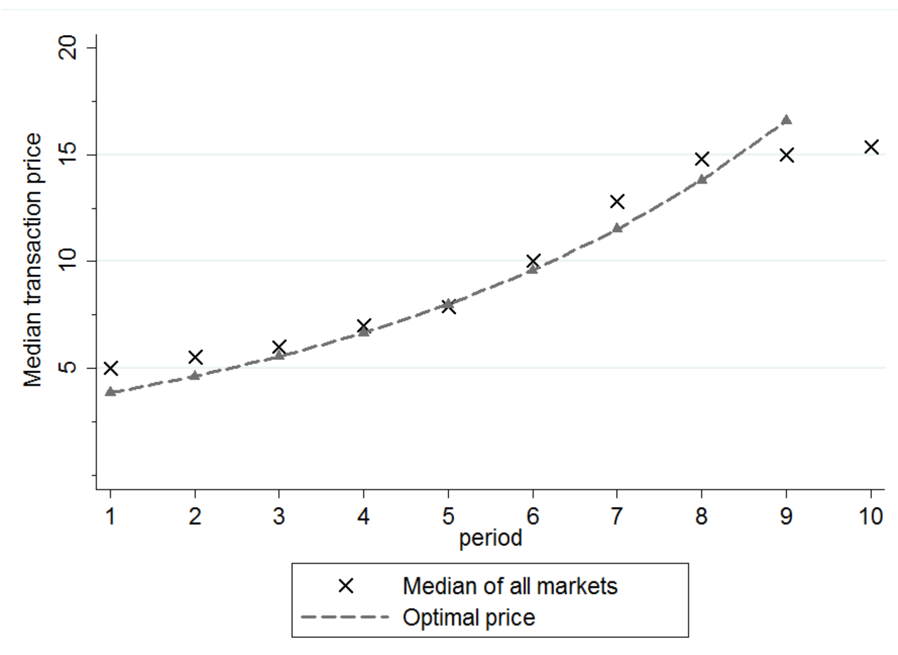

Figure 2 Scarcity rent of aggregated 10 markets of the Basic Treatment. Note: It is assumed that there is no trade in the 10th period, consequently, the theoretical price path ends in the 9th period.

The overall pattern is that sellers could realize prices above the theoretical level in the early periods and in periods 7 and 8 whereas in the ninth period the buyers realized prices lower prices. However, altogether one can observe a relatively strong attraction to the equilibrium prices.

In order to take a closer look at the data the first and second markets of each session are examined separately. Figure 3 contains the period-wise median price trajectories of the individual markets (gray lines) together with the corresponding treatment medians (thick black lines). The medians of the second markets display a monotonically increasing price path. However, when considering the first markets, only from period 2 to 9 does the price path conform to the central prediction of the standard theory.

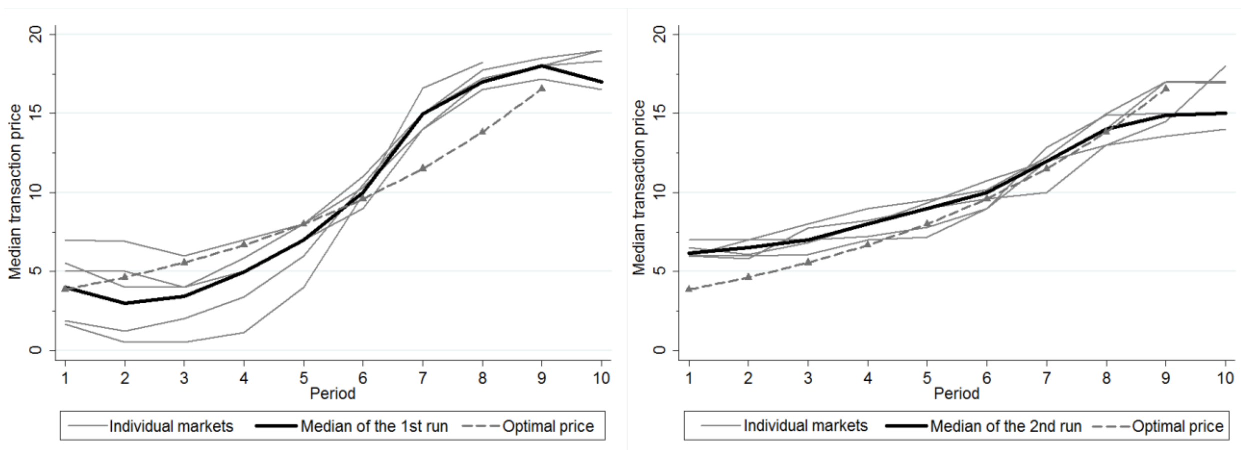

Figure 3 Median price trajectories in individual markets. Note: This figures show the period-wise median auction transaction values of the five individual markets respectively the treatment medians of the first markets (left panel) and of the second markets (right panel) of the Basic Treatment.

In the early periods of the first markets, buyers could negotiate lower prices, while, in the later periods, sellers were able to realize higher prices than the optimum suggests. The situation is reversed for the second markets: (Median) prices tend to be moderately overvalued in the earlier to middle periods, whereas, in the later periods, prices tend to be undervalued. In the second markets, the observed data closely follows the predicted path, whereas, in the first markets, there are greater deviations between the observed and predicted values.

Result 2: A learning process.

Brown et al. (2009) state that if learning creates a movement toward optimal choice this is *prima facie* evidence of bounded rationality in initial choices. They argue that highly rational subjects would not need to learn. We find that the data from the second markets are closer to the equilibrium than those in the first markets as shown in the price histograms (Figure 4). In particular, the mean absolute deviation from the optimal price drops in the second markets by 33.6%. The price-setting behavior, more precisely the distributions in the two markets, differ significantly at the one percent level in four out of the five sessions (rank sum test of prices). The only session in which we find no significant difference between the markets contains markets 7 and 8.[9] In this session the subjects chose prices very close to the equilibrium already in the first run. Consequently there was no vast learning potential although the histogram is even more sharpener around the equilibrium in market 8.

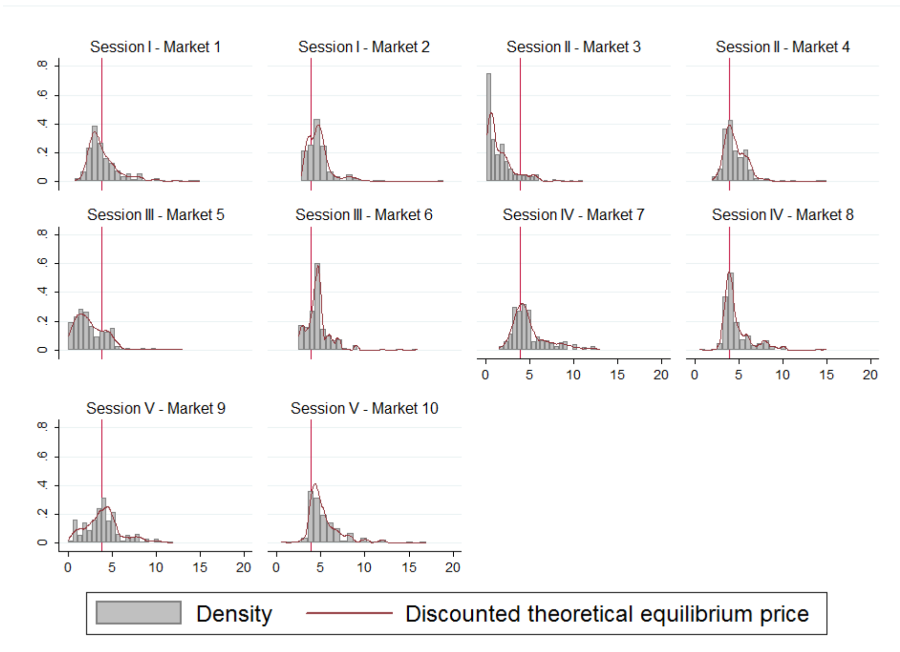

Figure 4 Price histograms with discounted data. Each market is depicted in a separate panel. Note: This is a discounted analysis and consequently the present value of the equilibrium price is constant over time. In the experiment there is a new optimal price (and quantity combination) in each period.

Result 3: Quantitatively validation by using a nonlinear regression model.

A quantitative analysis was conducted using least-squares estimations. The discrete price path can be described as

$$p_t = p_1 \cdot (1 + r)^{period-1}$$

[9] Two-sample Mann-Whitney-Wilcoxon test with transaction prices, p-value: 0.5122

Economically speaking, p_1 represents the scarcity rent in the first period. In the regression, p_1 is substituted by the coefficient β_1. In mathematical terms, the coefficient β_1 determines the price level and the slope of the estimated function. Setting the endogenous interest rate parameter to 20%, the estimation equation results to

$$p_t = \beta_1 \cdot (1.2)^{period-1} + \varepsilon$$

The results of the estimations are given in Table 2. Overall we find that the estimated confidence interval of the first, the second as well as of all markets covers the theoretical value of 3.852. The regression analysis uses the marginal prices across periods one to nine. Marginal prices are defined as the prices that occur in the last 30 seconds of each 3 minute period, since we wish to analyze settled prices.[10] The estimates in Table 2 are consistent with the hypothesis that the price increase is in accordance with an exponential growth law.

Table 2 Price regressions.

	price level β_1	95% Conf. Interval		N	R^2
1st markets	3.710 (0.086)	3.540	3.880	265	0.875
2nd markets	3.911 (0.035)	3.842	3.979	263	0.980
All markets	3.826 (0.044)	3.739	3.912	528	0.935
Theory	3.852				

Note: Standard deviations are in parentheses. We use a regression model without intercept. Therefore this modified R^2 cannot be interpreted as the common R^2. See Davidson and Mackinnon (2004) for a detailed discussion. N is the number of observations. Data is based on marginal prices of period 1-9.

[10] We assume that during each period we have a process towards the equilibrium price. Smith introduced a statistical parameter named coefficient of convergence (also known as "Smith´s alpha") to measure how close a market reaches to the theoretical equilibrium (Smith 1962). By calculating this coefficient by $\propto = \frac{\sqrt{1/n \cdot \sum_{i=1}^{n}(p_i - p^*)^2}}{p^*} \cdot 100\%$ we get a value of 16.94% as average for all markets and periods compared to (only) 3.75% when using the marginal prices. Therefore we argue it is reasonable to use prices which are more settled and where the price variation relative to the predicted equilibrium price is minimized.

Result 4: Aside from the final round, a decreasing quantity path.

The previous analysis of the prices is only one side of the coin, as the optimal allocation of resources is also of interest. We find that, aside from the final round, consumption declines over time, as shown in Figure 5. On average, the theoretically optimal quantity is exceeded in the first periods, whereas, the observed quantities fall below the optimal quantity in periods 6 to 8. The highest deviation is observed in the last round. However, by and large, a decreasing quantity path in accordance with the theory can be observed.

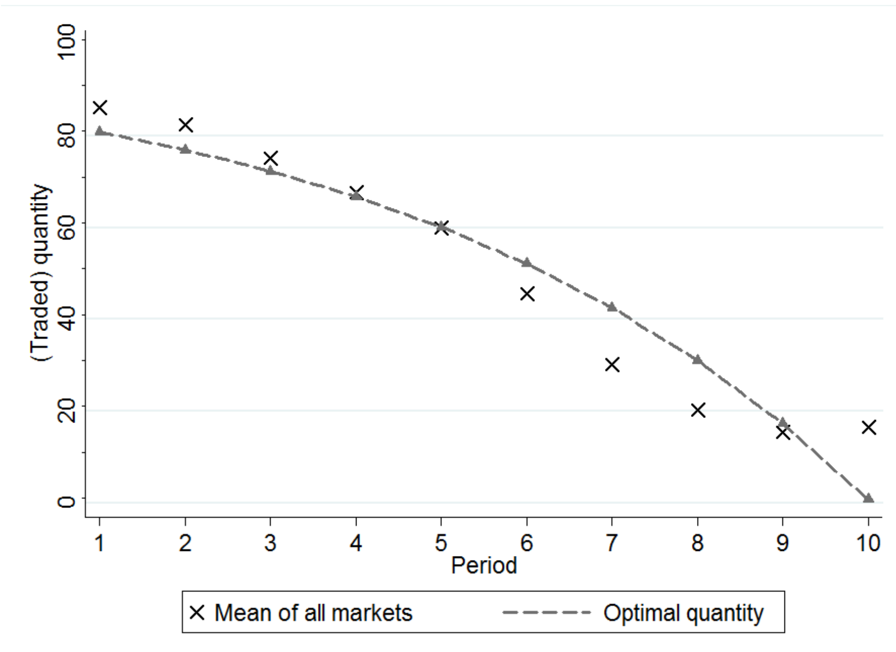

Figure 5 Aggregated average of the ten sellers. Data is based on 10 conducted markets.

The expectation that the entire stock is depleted before the game ends is widely satisfied. In 6 out of 10 markets, the stock of all sellers is depleted. In the remaining 4 markets, an average stock of 0.35 units (this corresponds to 0.7% of the initially endowment) remains after the final period.

Yet the more specific hypothesis that there is no trading in the final period has to be rejected. In 9 out of 10 markets, trading occurs in the last period with an average quantity of 16.4 units. Interestingly, trading activity in the last round is higher in the second markets than in the first markets. Of course, if there are units remaining in the market, it is then rational to sell them in order to maximize profits, even if the best strategy involved selling these units at an earlier time. However, this aspect should not be overvalued, as the remaining stock in the last period is around 3% of their initial stock or (only) 1.64 units per seller. There are other reasons why subjects might have been attracted to trade in the last period. For example, keeping the opportunity to act if attractive prices arise rather than being bored for the final 3 minutes of the experiment may be one such motivation.

The examination of the individual seller quantities in Figure 6 shows a surprising amount of heterogeneity. This, however, has no significant impact on the performance of the markets because only the aggregate sales are crucial for the market outcome. Actually some of the outliers significantly improve efficiency by compensating other players' deviation from equilibrium behavior.

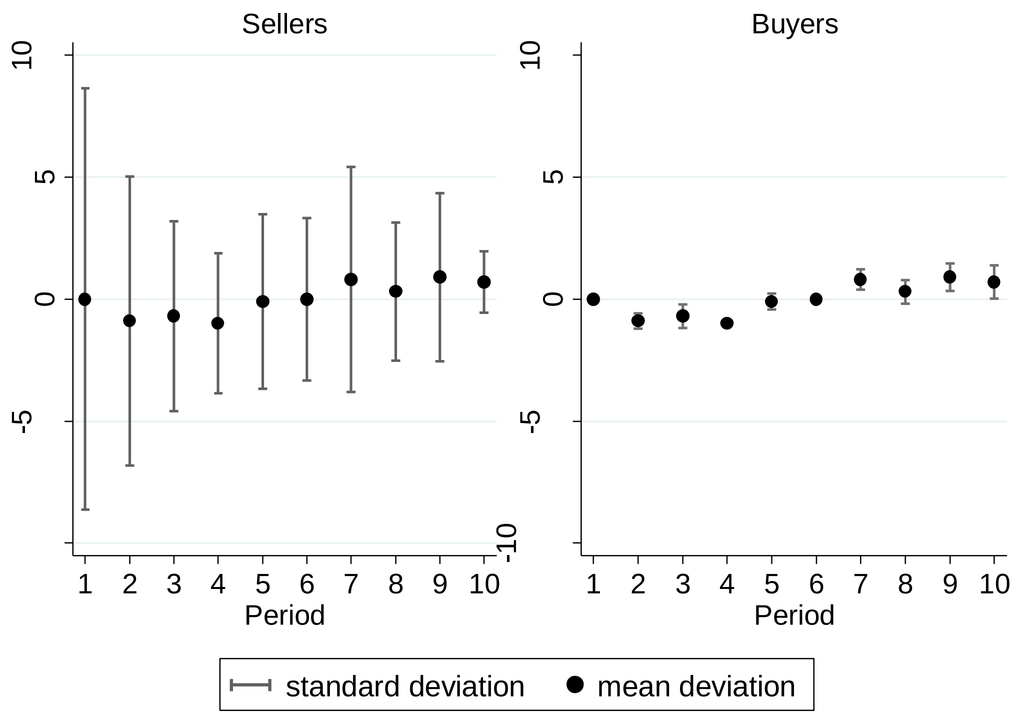

Figure 6 Mean deviation of individual quantities from its theoretical level (and the corresponding standard deviation)

For example, one subject[11] sold more than half of his stock in only one period. This was a an efficiency enhancing strategy for himself because the average price was above its theoretical level and for the market because the quantity traded was well under the optimum without his contribution. We regard these "equilibrating agents" as positive examples of entrepreneurs (Kirzner 1973) who notice that some prices are too high (or too low).

[11] Session 1, Market 2, Subject 07

Consequently, they perform an intertemporal arbitrage in order to realize additional profits. This, in turn, improves the market performance and thus serves the objective of an efficient allocation of the resources. Furthermore, the activity of the entrepreneurs shows that it is not necessary for an efficient market performance that all suppliers understand the logic of dynamic optimization. It suffices that some agents perceive that some additional profits can be realized by adapting their own supply to current market activities.

In contrast to the sellers the buyers show a remarkably homogeneous behavior. First, this quite plausible because buyers' optimal individual behavior is simpler than that of the sellers. Buyers do not have to take into account any intertemporal trade-offs. It suffices that their marginal utility in each transaction is smaller than the transaction price. Second, the homogeneity in buyers' consumption quantities is important for efficiency because it does make a difference whether one consumer with a high marginal utility buys the resource or another buyer with a low marginal utility.

Analogous to the procedure with the price regression, one can show that the quantities are in accordance with the theoretical equation. The quantity path can be described with

$$x_{total,opt} = 100 - 19.26 \cdot (1.2)^{period-1}$$

The optimal factor 19.26 determines the quantity level and the slope of the function. As we want to compare this value with the data set, the estimation equation results to

$$x = 100 - \beta_2 \cdot (1.2)^{period-1} + \varepsilon$$

For instance, the function would be flatter and start on a higher level if the estimated value of β_2 is below the theoretical value. The results of the regression analysis are given in Table 3. It can be shown that there is no significant difference between the optimal value and the estimated coefficients of the first, the second as well as of all markets.

Table 3 Quantity regressions.

	β_2	95% Conf. Interval		N	R^2
1st markets	18.585 (0.569)	17.441	19.730	50	0.955
2nd markets	19.967 (0.667)	18.626	21.308	50	0.948
All markets	19.276 (0.442)	18.399	20.153	100	0.950
Theory	19.26				

Note: Standard deviations are in parentheses. We use a regression model without intercept. Therefore this modified R^2 cannot be interpreted as the common R^2. See Davidson and Mackinnon (2004) for a detailed discussion. N is the number of observations. Data is based on the aggregated market quantity of each period and each market.

Result 5: High efficiencies in the market.

One fundamental question of the theory of exhaustible resources is whether one can expect that the market ensures an efficient intertemporal allocation of resources (Siebert 1970). Although this question is hard to answer in real markets, with experimental data it is relatively easy to perform this analysis. By dividing the realized producer and consumer surplus by the total possible surplus[12], a market efficiency of 97.95% is the average result. In line with the mentioned learning process, higher efficiencies occur in the second markets.

In large part, these high efficiencies are due to the design of the market institution.[13] Yet there are three sources of efficiency losses in the current treatment design. First, the total surplus is reduced when units are not being sold within the ten periods. Second, the buyer surplus is reduced if the buyers consuming an unequal amount of units[14]. Finally, the seller

[12] Note: As mentioned in chapter 3, for simplifying reasons there is no interest rate implemented for the buyers as it is independent for their decision-making. Consequently, there exists an asymmetry when using the original profits by calculating the overall efficiency. Therefore, the efficiency analysis is made on the basis of a present value consideration to make the numbers for both groups comparable.

[13] Various publications are dealing with this finding of high efficiencies in double auction markets, starting with Smith (1962).

[14] Because each buyer has the same utility function it is also optimal that the buyers are consuming the same amount of resources. Otherwise a buyer who already consumed several units is getting a smaller utility per unit, whereas another buyer could earn a higher value by consuming e.g. the first unit instead.

surplus is reduced if the aggregate intertemporal allocation of resources deviates from the theoretical solution.

Assume a hypothetical market where no efficiency losses arise from the first two cases but only through trading the same amount of units in each period. In that case, an efficiency benchmark results to 92.81%. As a next step, we calculate a relative efficiency as:

$$\eta^*_{\mathrm{eff}} = \frac{(\eta_{\mathrm{eff}} - \eta_{\mathrm{benchmark}})}{(100\% - \eta_{\mathrm{benchmark}})}$$

The results for the absolute and relative efficiencies for the first and second markets are presented in Table 4.

Table 4 Absolute and relative market efficiencies.

	absolute efficiency η_{eff}	efficiency benchmark $\eta_{benchmark}$	relative efficiency η^*_{eff}
All markets	97.75%		68.63%
1st markets	96.93%	92.81%	57.32%
2nd markets	98.56%		79.95%

The efficiencies are expressed on a scale from 0 to 100%, with 100% representing the theoretical maximum efficiency. In the case of the relative efficiency, the 0% corresponds the efficiency benchmark. For instance, in case of the second markets, nearly 80% of this range is achieved.

6 Discussion

Although the overall good results from the laboratory were quite surprising, there are some aggregate and many individual deviations from the theoretical predictions. Furthermore, it is disputable whether there exist other approaches that can explain the data better than the standard theory.

From a theory testing perspective as well as from a climate politic point of view it is interesting to see whether there are systematic distortions like a premature exhaustion of the resource.[15] The literature in experimental economics being applied in resource economics is telling us very little, apart from Veldhuizen and Sonnemans (2011) finding a small tendency for resources to be exhausted prematurely. Figure 7 shows some excessive consumption of the resource in the first half of the experiment in the first markets (on average 14.5% more compared to the optimum in the first 5 periods). However, after a learning process, in the second markets, the consumption approaches the equilibrium and even falls below the optimum, which means the resource is being depleted too slowly (7.05% less compared to the optimum in the first 5 periods).

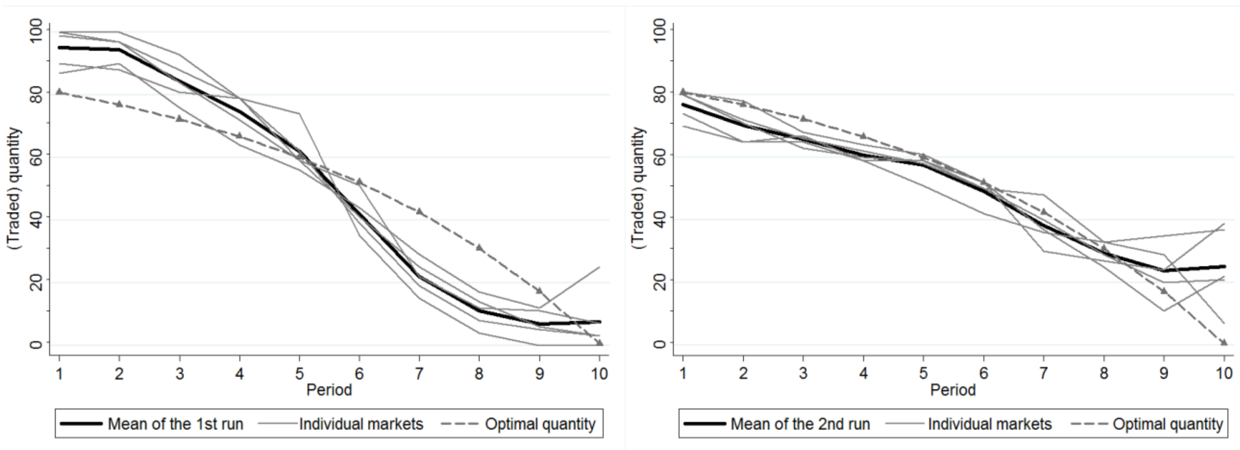

Figure 7 Traded quantity in individual markets. Note: This figures show the period-wise mean quantity volumes of the five individual markets respectively the treatment mean of the first markets (left panel) and of the second markets (right panel) of the Basic Treatment.

As we have already discussed above, sellers' behavior is quite heterogeneous (see Figure 6). Thus, it seems highly implausible that each seller's behavior can be interpreted as the result of one and the same intertemporal optimization problem. Obviously, the sellers either have different assessments of their trading opportunities or some of the sellers simply make mistakes. Either way, market performance is very close to efficiency. Our interpretation is that this experiment is just another example of ecological rationality (Smith 2003): Presumably, no single seller conducted a formal optimization calculation. Yet there are some players who understand the intertemporal dependency of prices and have a good assessment of a reasonable price path. Realizing that prices are too low (or too high), they adapt their

[15] Already Hotelling (1931) emphasizes in the first sentences of this origin article on the aspect if there is an excessive extraction of resources.

individual supply quantities in an entrepreneurial way in order to sell their units when prices are high. Such an individual reallocation of supplies moves the economy in the direction of the theoretical equilibrium.

The effect of these entrepreneurial adaptations is, however, imperfect as Figure 7 shows: there remains a difference between the equilibrium behavior and actual play in all markets. Yet this fits quite well into our interpretation of observed behavior as an example of ecological rationality. Since all participants are not perfectly rational and entrepreneurial activity is guided by rough estimations of intertemporal price differences, one can hardly expect that all first-order conditions of dynamic optimization are exactly fulfilled. Real entrepreneurial activity moves the economy close to efficiency but typically does not realize it perfectly.

Hitherto, we have ignored the fact that deviations of actual resource consumption from its theoretical level in early periods changes optimal consumption in later periods. As an example: When all subjects are selling one unit less in the first period than the optimum, the "new" optimum path in the second period has to be updated and would start at a lower price level. Therefore, a literally optimal adaptation should take this into account and price as well as quantity paths might be closer to such a permanently updated optimal path than to the Hotelling path.

To test this, we calculated this discontinuous, conditional price path for all markets and all periods by taking the actual quantities into account. Afterwards, we compared the deviations of both the Hotelling path and the updated optimal path with the data. However, it shows that the Hotelling path stays the best reference.[16] Examining the experimental design, this result is not surprising anymore: During the experiment, the subjects were informed about their own remaining stock, although not about the stock remaining in the whole market. However, the latter parameter is the key value which is needed as input for the conditional path.

Another explanation for the difference between equilibrium play and actual play might be to explicitly model boundedly rational behavior. Since "[o]ne problem is the spectacular contrast between the sophisticated mathematical apparatus required to solve the optimal

[16] The mean absolute deviation is about 11% higher in the case of the updated optimal path. Appendix A shows a box plot of the deviations from the original and the conditional price path to the data.

consumption problem and the mathematical imbecility of most consumers" (Carroll 2001, p. 29), it looks promising to abandon neoclassical maximization in the theoretical explanation altogether. In the literature on Double Auctions it is typically assumed that players are either perfectly rational or have no intelligence at all.[17] Instead of using such extreme assumptions, it could be a useful approach to take a middle course. Recent research shows that the behavior of subjects in economic experiments can often be explained a particular model of bounded rationality, i.e. the quantal response equilibrium (QRE; McKelvey and Palfrey 1995, 1998). Here, it is assumed that people act consciously and purposefully, but they also make mistakes. In QRE each possible action is chosen with a strictly positive probability, but actions with higher payoffs are chosen with higher probabilities than poor choices. However, to proceed with such an approach means to advance the concept of QRE substantially. Because of the continuous nature of the auction, multiple subjects interacting with one another and, certainly, a large space of actions, it looks much like a challenging approach with a serious problem of complexity so that it is beyond the focus of this study and represents an avenue for further research[18].

7 Conclusion

Empirical research on the validity of the equilibrium theory of resource extraction has not yet led to a consensus. The majority of studies rejects the basic model but there is still an important minority of studies getting the opposite result. We believe it is fair to say that practically all studies suffer from substantial methodological problems. In particular the basic assumptions of Hotelling's model (a publicly known and exogenously given resource stock, the absence of business cycles, political shocks, ...), the inability to measure the empirical scarcity rent and the violation of the ceteris-paribus rule may serve as an explanation for the moderate empirical success of the theory. By conducting economic experiments, it is possible to circumvent most of these problems. Accordingly, it is our objective to provide such a test.

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[17] Gode and Sunder (1993) replace human traders with zero-intelligence programs that submit random bids and offers.

[18] The first theoretical approach to apply the concept of the QRE model in a double auction is made by Neri (2010). However, "only" a one-unit, uniform price double auction is analyzed. Nevertheless, Neri concludes that the QRE model appears as an appealing tool for analyzing double auction data.

Our experiment largely confirms the basic results of the standard theory of resource extraction:

- We find an increasing price path.
- By and large, this price path shows a convex shape. Furthermore, the median prices in our experiment are surprisingly close to the theoretical prediction.
- We find a decreasing consumption path which, again, is largely in accordance with the predicted pattern.
- We always find high degrees of efficiency (always above 95% and in the second markets even above 98%).
- The individual consumers' behavior is very close to the theoretical prediction.
- The individual behavior of the suppliers varies much more. Yet this is not much of a problem because, in equilibrium, the suppliers are in different with respect to the time of selling. On aggregate, the behavior of the suppliers is, again, close to the theoretical prediction.

Of course, we have to acknowledge some shortcomings of our study. Not really surprising, the data's fit to the theoretical prediction is not perfect and there is non-negligible variation between the prices in the different markets and sessions. This is particularly true for the first markets in each session. Next, we find learning effects: in the real world markets for exhaustible resources, however, there is no such thing as "the second market in a session". Consequently, the worse results of the first markets might be more closely related to real world markets. This, however, is not necessarily true because the lack of a second period may be substituted by getting an economic education or by hiring economic experts. Furthermore, it is not necessary that all suppliers understand the logic of Hotelling's rule. It is sufficient that some of the suppliers understand it and that deviations from the Hotelling path provide an opportunity for gaining additional profits for those sellers who recognize it.

We interpret our findings as an example of the ecological rationality of markets (Smith 2003). In order to realize a near efficient market performance, it is not necessary that all players have perfect information and that all players are perfectly rational. Quite the contrary, the institution of free market exchange serves as a substitute for perfect rationality and perfect information so that boundedly rational subjects with imperfect information are able to achieve next to efficient results. As a consequence, we believe that our experiment provides good reason to reinforce our trust in the market based intertemporal allocation of exhaustible resources.

Finally, there are several open questions for future research. First, it is not yet clear how robust our results are. Obviously, there is a need for testing the impact of parameter variations in our experiment. It may be even more important to test the performance of other market designs than the continuous double auction. Second, our laboratory market ignores many of the additional features of real world markets of exhaustible resources. For example, we do not know how unexpected resource findings affect the behavior of suppliers and consumers. It might well be the case that such events induce overoptimistic expectations regarding future discoveries of new mines. Then, how can one account for changes in time preferences or in interest rates and how can people living nowadays anticipate the development of interest rates in the years to come? Last but not least, other versions of the basic model, e.g., with an inclusion of backstop technologies have to be tested as well. Although it is obvious that there are still many open questions, we believe that our paper shows the general relevance of the economic forces described in Hotelling's model of resource extraction.

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Data Source of Figure 1: Oil prices and CPI from BP (www.bp.com), Coal (1972-2010) and Gas from the US Energy Information Administration (www.eia.gov), Coal prices (1900-1971) from the National Mining Association (www.nma.org).

Appendix A

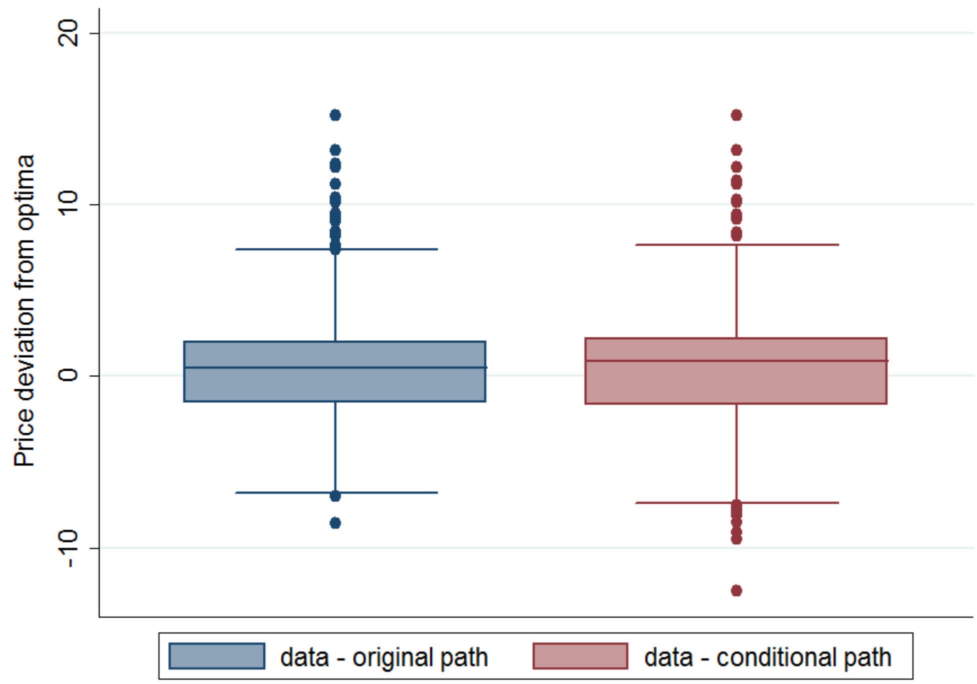

Figure 6 Comparison of the price deviation to the original path and the conditional path.